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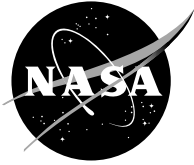
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## Abstract

Room temperature measurements of the turn-off time ( $t_q$ ) are reported for several packaged, npnp developmental power thyristors based on 4H-type SiC and rated 400 V, 2 A. Turn-off is effected by a 50 V pulse of applied reverse voltage, from a state of a steady 1 A forward current. Plots of  $t_q$  against the ramp rate ( $dV_{AK}/dt$ ) of reapplied forward voltage are presented for preset values of limiting anode-to-cathode voltage ( $V_{AK,max}$ ). The lowest  $t_q$  measured was about 180 ns. A rapid rise of these  $t_q$  curves was observed for values of  $V_{AK,max}$  that are only about a fifth of the rated voltage, whereas comparative  $t_q$  plots for a commercial, fast turn-off, Si-based thyristor at a proportionately reduced  $V_{AK,max}$  showed no such behavior. Hence these SiC thyristors may have problems arising from material defects or surface passivation. The influence the R-C-D gate bypass circuit that was used is briefly discussed.

## Introduction

The superior thermal conductivity, breakdown electric field, saturation drift velocity and wide bandgap of 4H-type silicon carbide (table I) continue to motivate intense efforts to exploit this material for high temperature capable, fast-switching power devices. Years have passed since the first demonstrations of vertical npnp thyristors in 4H-SiC (refs. 1 and 2), still the development of large-area power devices continues to be hindered by crystalline defect problems, in addition to the fact that SiC has no naturally passivating oxide. Although there exist studies of the turn-on process in such thyristors (refs. 3 and 4), data reports on turn-off from a steady forward conduction state are scarce. This paper reports turn-off time ( $t_q$ ) measurements at room temperature on experimental npnp thyristors built on n-doped 4H-type silicon carbide substrates. These devices, packaged on gold plated kovar TO-220 headers with welded lids, are nominally rated 2 A, 400 V forward blocking and are the products of Cree Research, Inc. (ref. 5). Some  $t_q$  data is reported in (ref. 5), but for zero applied reverse voltage. No information is available on the crystalline defect (e.g., micropipe) statistics, the doping profiles, or on the surface passivation for these devices.

## Method of Measurement

Except for details of the gate drive, the  $t_q$  measurement circuit used is fully described in the NASA/CR—2006-214260. Briefly, this circuit uses a fast MOSFET switch to divert the current from an inductively driven current source away from the thyristor under test (TUT), while simultaneously applying a constant reverse bias voltage of adjustable amplitude and duration to the TUT. Following the reverse bias period, the current from the source is switched to an adjustable array of capacitors in parallel with the TUT, generating a voltage ramp of controlled slope across the TUT. The height of this ramp is limited by an adjustable array of energy absorbing Zener diodes.

As the duration of the reverse bias is decreased, with the other parameters kept constant, a point is reached where the reapplied voltage causes the TUT to turn on again. The  $t_q$  is then the time from the zero crossing of the current to the zero crossing of the reapplied voltage ramp. An illustration of this measurement process is given in figure 1. The circuit allows a cyclic repetition of this measurement, such that a reliable value for  $t_q$  can be obtained.

It is well known that impedance conditions in the gate firing circuitry have a great effect on the  $t_q$ . This is due to the influence of any gate bias on minority carrier injection at the p-n junction included in the gate firing circuit loop. The reapplied voltage ramp induces a capacitive displacement current through the TUT and hence a minority carrier injection at any p-n junction oriented in the forward direction, such as the junction involved in the gate firing circuit. Indeed, both this injection effect, and hence the  $t_q$ , can be reduced by bypassing this junction or by the application of a low level reverse bias to this junction at the start of the reapplied forward voltage. Both bypassing and such a bias were effected here by use of a small (5 nF) gate capacitor; however, see later discussion. A bypassing diode was finally added to protect this junction from the transient multiampere reverse breakdown currents induced by the sudden application of reverse voltage to the TUT.

Since in the thyristors tested here had their gates connected to the n-layer next to the p-layer of the anode (the so called 'anode gate') and the cathode was grounded, the gate firing circuit was at the high potential of the anode and had to be isolated from ground. This was done by a small transformer, based on a high frequency ferrite core. Capacitive effects to ground through this transformer were not evaluated. A diagram of the gate firing circuit is shown in figure 2.

### Experimental Observations

Initially, 5 SiC thyristors of the same structure and nominal ratings were selected for measurement, but 2 of these devices failed early during measurement, leaving only the 3, whose data is shown in figure 3. The histories of these devices were not identical, however. Thyristor ST/SQR-1 had been aged for 1000 hr at 350 °C by the manufacturer (Cree Research, Inc.), and thyristor TC/SQR-17 had been subjected 5 times to a thermal shock cycle (Mil-Spec 202F, method 107F) from -65 to 350 °C, whereas thyristor VG/SQR-3 had no prior history of such aging or testing.

A  $t_q$  below 400 ns could be obtained in all the tested devices and below 200 ns for the VG/SQR-3, provided the rate ( $dV_{AK}/dt$ ) of forward reapplied voltage was sufficiently low. For low rates below about 200 V/ $\mu$ s, the retriggering would normally be on the rising slope of the reapplied forward voltage ( $V_{AK}$ ), provided its limiting value  $V_{AK,max}$  was set sufficiently high. Under these conditions, the  $V_{AK,max}$  has no effect, explaining the confluence of the  $t_q$  curves for a particular device at low  $dV_{AK}/dt$ . As  $dV_{AK}/dt$  and  $t_q$  increase, retriggering is normally at the preset limiting voltage  $V_{AK,max}$  and the curves separate according to this limiting voltage.

The second notable observation is that the rate of increase of  $t_q$  with  $dV_{AK}/dt$  becomes very large once some value of  $V_{AK,max}$  is exceeded. Qualitatively, this says that above some value of  $V_{AK,max}$  even below the maximum dc rating, the thyristor can not be kept off, except possibly at uselessly low rates of reapplied forward voltage. Such behavior may well be expected for  $V_{AK,max}$  close to the absolute dc rating of the device. Here, however, 72 V is only but a fifth of the absolute rating of these SiC thyristors. To get more insight into this problem, a comparative plot of the  $t_q$  of a fast turn-off Si thyristor is included in figure 3. The MCR2150A is an 800 V, 15 A commercial thyristor (now discontinued). And at  $V_{AK,max}$  of 153 V, this device is also being operated at about a fifth of its absolute rating. But there is no tendency yet for its  $t_q$  plot to curve upward. For the MCR2150A, the nearly uniform shift up of the 153 V curve as compared to the 63 V curve is anomalous (unknown cause), since a 72 V curve (not plotted) had no such consistent shift relative to the 63 V curve shown.

### Summary and Discussion

Turn-off times ( $t_q$ ) were measured at room temperature for several developmental thyristors based on 4H-type SiC and depending on the rate ( $dV_{AK}/dt$ ) of reapplied forward voltage, values below 200 ns were observed. Plots are presented of  $t_q$  versus  $dV_{AK}/dt$  up to 3000 V/ $\mu$ s, for preset values of limiting anode-to-cathode voltage ( $V_{AK,max}$ ). Turn-off was always effected from a steady state of 1 A forward conduction by a reverse applied voltage pulse of 50 V and of a duration according to the  $t_q$ .

A rapid upward curvature of these  $t_q$  plots is evident in figure 3 for values of  $V_{AK,max}$  that are only about a fifth of the absolute rating ( $\sim 400$  V) of these SiC thyristors. This strongly suggests a problem with either surface passivation or else a basic SiC defect problem, such as micropipes (severe screw dislocations). When a commercial fast turn-off, Si-based thyristor was tested at a proportionately low  $V_{AK,max}$ , no such upward curvature of  $t_q$  was observed. This further points to the existence of a materials or device fabrication problem in these SiC devices. Nevertheless, the potential for an enormous reduction in turn-off time by going to SiC, as compared to the fastest Si thyristors, is evident in figure 3.

As cautioned above, impedance conditions in the gate firing circuitry have a great effect on the measured  $t_q$ . Initially, gate bypass capacitors of 5 nF and higher were tried, without the diode (see fig. 2). This capacitor bypasses displacement currents, induced by the reapplied forward voltage ramp, around the anode-to gate p-n junction, thus hindering minority carrier injection there and hence reducing  $t_q$ . Indeed, this capacitor can get charged by the reverse current transient (caused by the sudden application of a reverse bias), up to the breakdown voltage of this junction. Besides making the gate more difficult to fire, such an overly large ( $>5$  nF) ‘cheating’ capacitor was found to cause under certain conditions, a double valued  $t_q$ ! The cause is simply that while this capacitor retains sufficient charge to significantly reverse bias the said junction, it is difficult for the rising forward voltage to retrigger the thyristor. However, once this charge is gone, retriggering can be easy. Also, if the duration of the reverse bias pulse is very short, the capacitor has less influence and retriggering can again occur. A value of 5 nF gave acceptable performance, especially after the diode was added. The purpose of the diode is to protect the anode-gate junction from the transient multiampere reverse breakdown currents induced by the sudden application of reverse voltage to the thyristor. After observing that thyristors failed during measurements usually had deteriorated anode-gate junctions, the diode seemed desirable. With the diode in place, the capacitor still bypasses to some extent the ramp-induced currents, but the problem of two values for  $t_q$  was gone.

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TABLE I.—APPROXIMATE MATERIAL PROPERTIES OF 4H-TYPE SiC AND Si\*

	4H-SiC	Si
Band gap (eV)	3.26	1.12
Breakdown electric field (V/cm)	$2.2 \times 10^6$	$2.5 \times 10^5$
Thermal conductivity W/(cm K) (at room temperature)	4.9	1.5
Saturated electron drift speed (cm/s) (for $E > 2 \times 10^5$ V/cm)	$2 \times 10^7$	$1 \times 10^7$

\*Data provided by Cree Research, Inc.

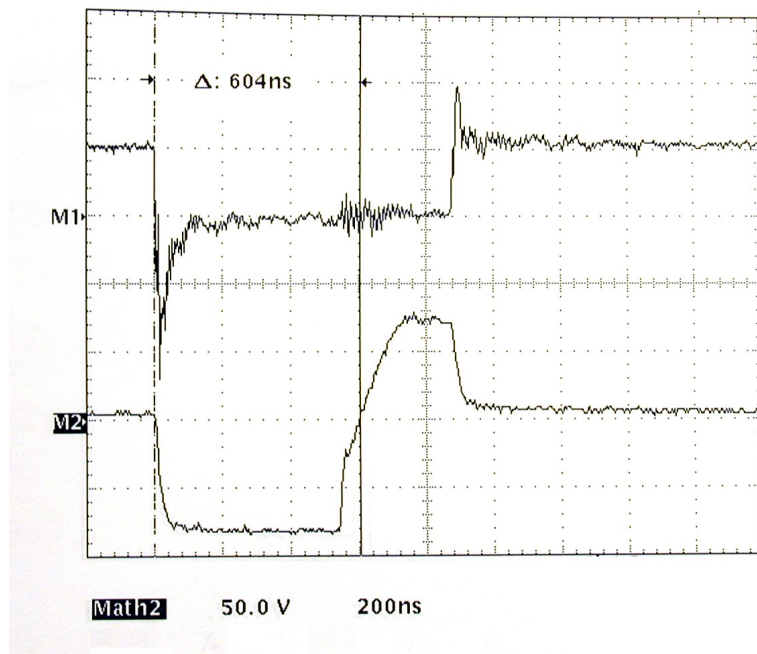


Figure 1.—Typical current (upper) and voltage (lower) waveforms observed during  $t_q$  measurement. Here the thyristor turns on spontaneously on the plateau of maximum reappplied voltage. Turn-on may also occur on the rising slope of the reappplied voltage.

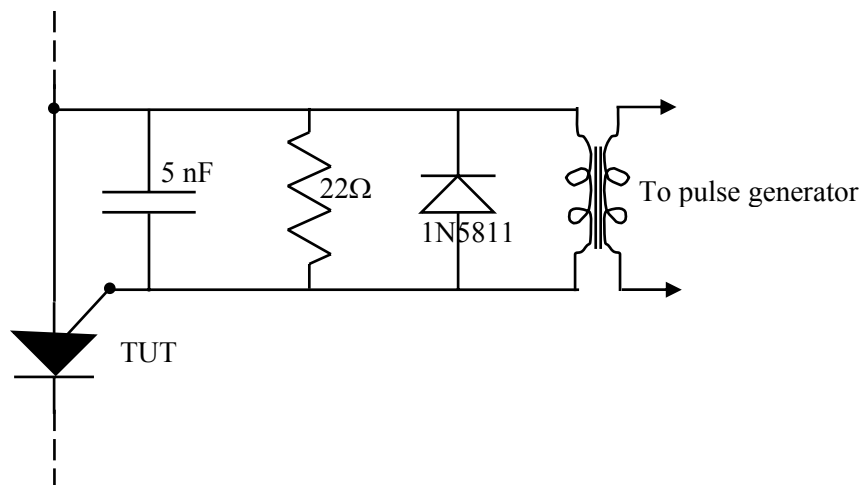


Figure 2.—Gate firing circuit used to measure  $t_q$  of the SiC thyristors. The diode was added to protect the gate junction from breakdown during the reverse current transient. The pulse generator has an output impedance of  $50\ \Omega$ .



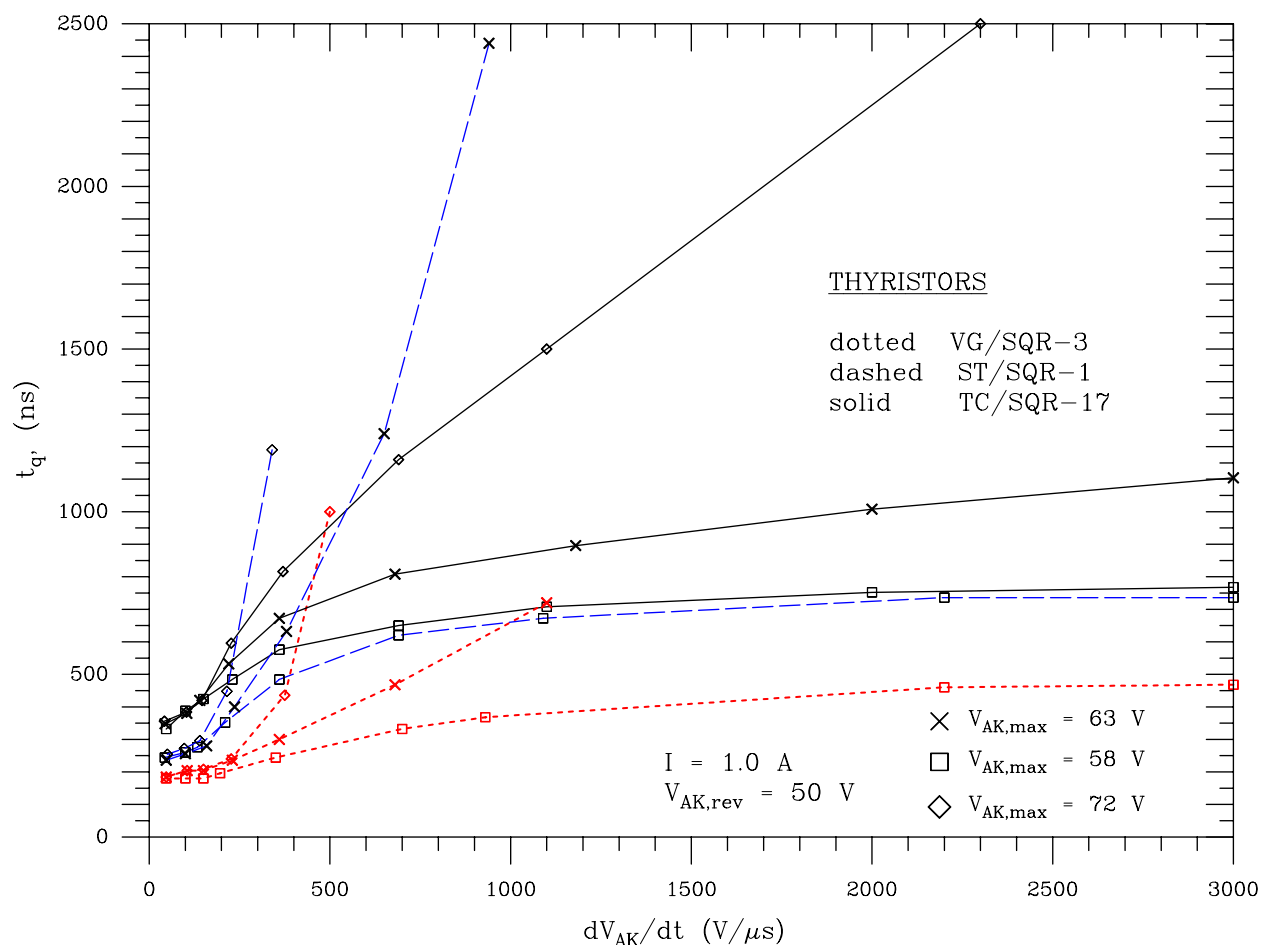


Figure 3.—Turn-off time ( $t_q$ ) as a function of the rate of rise ( $dV_{AK}/dt$ ) of reapplied forward voltage for three 4H-type SiC thyristors, using the gate trigger circuit shown in figure 2. In all cases, the initial forward current was a steady 1 A and turn-off was effected by a reverse applied voltage ( $V_{AK,rev}$ ) of  $-50 \text{ V}$ . For each thyristor, results are shown for 3 limiting anode-to-cathode forward voltages ( $V_{AK,max}$ ).

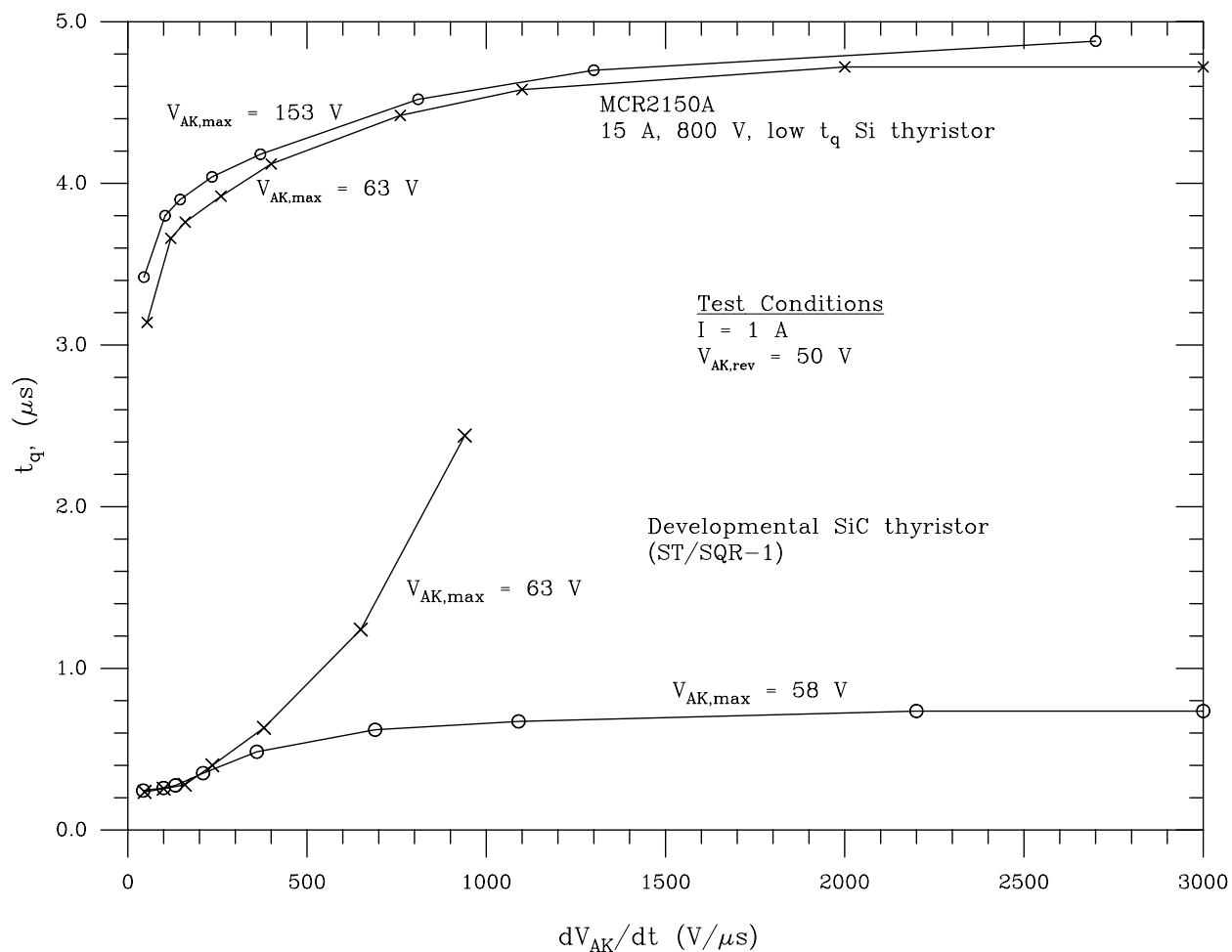


Figure 4.—Comparative plots of  $t_q$  for a fast turn-off, commercial Si thyristor and the ST/SQR-1 developmental 4H-type SiC thyristor. The cause for the persistence of a vertical separation of the two MCR2150A curves for low values of  $dV_{AK}/dt$  may be experimental error.

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